ROBOTIC SUPPLY OF SUPPORT EQUIPMENT FOR CREWED MISSION TO MARS

M.B. Velante[1,2], K. Schreck[1,2], N. Djordjevic[1], E. Ortiz[2], A.H. Djamshidpour[2], V. Shum[2], R. Brill[2]

[(1)]*Lockheed Martin Space Systems Company, 1111 Lockheed Martin Way, Sunnyvale, California, USA, 94089*
matthew.b.velante@lmco.com, nik.djordjevic@lmco, keith.r.schreck@lmco.com
[(2)]*San Jose State University, Department of Mechanical and Aerospace Engineering,*
One Washington Square, San Jose, California, USA, 95152-0087
ortize@slac.standford.edu, aminh110@yahoo.com, vshum12@gmail.com, rjbrill@pacbell.net

ABSTRACT

This paper addresses robotic aspects for Mars missions in preparation for a Crewed Mission to Mars Program, based upon requirements defining a mission emphasizing use of the International Space Station as a major resource in execution of the mission [1,2].

The system-level solution for this mission is described in three phases. Focusing on the first phase, two robotic missions will deliver to the Martian surface supplies and support equipment for the mission duration. The departure of the two robotic missions will take place at the ISS.

The staging of two robotic missions relies on proven technology and lessons learned in trans-Mars injection, aero-breaking, descent, and Earth re-entry technologies. Trade studies for executing a multi-year, multi-element, international, mission to Mars were performed based upon optimum performance parameters, and technology readiness levels.

Emphasis is placed upon reliable and proven techniques for mission success for human landings on Mars.

1. INTRODUCTION

New initiatives by President George W. Bush and the Commission on Implementation of United States Space Exploration Policy has made human and robotic exploration of space a priority for NASA and the international space community [3]. The Crewed Mission to Mars Program (CMMP) is designed to address these initiatives and provide a total system solution for a future manned mission to Mars.

1.1 Crewed Mission to Mars Program (CMMP)

CMMP was designed to provide the international space community with viable options for sending a crew to the Martian surface to conduct science and Martian base operations. Implementing proven techniques with robust technology provides a margin of safety for the crew and the mission.

2. MISSION CONCEPT OF OPERATIONS

Many concepts for missions to Mars have been proposed under a variety of mission requirements and timeframes. Detailed in section 2.1 are the requirements and mission specifications for the CMMP.

2.1 CMMP Mission Requirements

The baseline requirements for this mission are outlined in the six following points:

1. The crew must land on Mars within 10 years of the authority to proceed date of Jan 1, 2015.
2. Six person crew to consist of three men and three women.
3. Crew shall be capable of safe living on the surface of Mars for a minimum of 62 Earth days.
4. Crew shall be capable of safely returning to Earth at any point during the mission.
5. Crew shall be capable of two way communication to Earth at all times during the mission. Allowances of two hours per day communications blackout due to trajectory characteristics are allowed.
6. Crew shall be capable of safe meaningful scientific exploration, including water and ice, in addition to others. Crew shall have access to locations within 500 km radius of the base of operations.

These primary mission requirements were utilized and additional considerations that placed limitations or constraints on the primary requirements are presented here.

1. Use of International Space Station (ISS) on-orbit and ground support hardware, software, operational procedures, Mission Operations (including Ground Control facilities), training facilities, Program Management teams and engineering personnel.
2. Overall cost of the mission, which shall be minimized to the greatest extent possible.
3. Safety of the crew shall be maximized to the greatest extent possible.

4. Maximize simplicity, robustness, and reusability of concept, hardware and software.
5. All technology implemented in mission design must achieve Technology Readiness Level (TRL) 7 by year 2015 [4].

Use of, and level of involvement of the ISS in the planning, development and operation of this mission is left as an open requirement in the mission. To minimize overall system cost and to develop a robust system use of common elements is being considered of highest priority to rapidly mature planetary technology.

The CMMP is a three-phase mission to successfully land a crew on Mars, stay for a period of time and return them safely to Earth. The first phase is of primary interest in this paper as it establishes the structure and the outline of the mission process. This paper will cover the events critical to this phase of the mission and cover main points for Phases 2 and 3.

2.2 Phase 1: Robotic Supply Mission to Mars

In Phase 1 of the mission, all of the major components of the entire system are combined together and prepared for the entire mission. This phase incorporates the supply and support elements; Mars habitat and laboratory, planetary power reactor (PPR), Mars Ascent Vehicle (MAV), communications satellites, rovers, propellant, and supplies for the duration of the mission. All these elements will be staged to launch to the ISS at regular intervals atop four Energia boosters each with 100 metric ton launch capabilities. The cargo carriers for these elements from Low Earth Orbit to a Trans-Mars Injection (TMI) orbit are two Bimodal Nuclear Thermal Rockets (BNTR) vehicles. To ensure safe operation and handling of the nuclear engines, fuel cores will be launched separately from the reactor and only inserted into the vehicle in orbit at the ISS after full vehicle check outs and system tests have been performed.

Fig. 1. Proposed Energia Heavy Lift Launch Vehicle with Prototype CTV Elements [5]

The ISS plays the keystone of the entire mission. In its completed state by the launch window for this mission, the station will be able to service, test and assemble many of the mission elements to ensure operation before launch of the cargo elements. As the assembly and testing proceed new techniques that are crucial to future missions can be evaluated including, construction, testing, and repairing the elements needed for the long mission.

Launching of the elements is on a staggered timetable from their launch site at Baikonur. Assembly of the mission elements can occur on the ground, however larger elements such as the BNTR's must be assembled on orbit at the ISS. All components can then undergo rigorous final testing to ensure they survived the harsh launch conditions before committing them to this multiyear mission.

After final verification of all systems on each craft the two cargo vehicles will depart Earth's orbit September 14, 2022. The BNTR engines will provide high thrust propulsion and power to transport all these elements to Mars. Arrival occurs on October 2, 2023, where cargo elements will separate from the BNTRs and prepare for direct aerocapture to the landing site using parachutes and liquid oxygen/methane reaction control thrusters.

Upon determination of successful landing of the habitat and MAV, two small robotic trucks will deploy and travel a minimum of 500 meters away from the base camp. Integrated with each truck is an 80 kW nuclear power plant, which will provide the needed power for the habitat and laboratory, the in-situ propellant development facilities and the MAV, and provide power for high bandwidth data transfer with the satellites and the crew. One satellite will be deployed and phased with the communication elements on each Cargo Launch Vehicle (CLV) and take up orbit around the planet to provide continuous communications coverage amongst the astronauts on the surface and Earth.

Two un-pressurized rovers with autonomous capabilities will deploy from the vehicles and begin scouting the area around the base camp for signs of water and marking locations of scientific relevance for the crew to investigate later. Once the power plants have been confirmed operational, the in-situ propellant development will begin. This process will generate the propellant for the MAV to return to orbit upon completion of the crews' surface stay. The propellant development will also generate propellant to refuel the rovers used to transport the crew over the surface. The activities of all these components will be closely monitored via the communication network. The crew launch in late 2024 will not commence until all of the mission sequence events here have been completed.

As the base camp is being established on Mars, the power generators begin operations, propellant generation begins, and the rovers begin to explore, preparation on Earth will continue to ready the supplies and prepare another BNTR to transport the six person crew to Mars in late 2024.

2.3 Phase 2: Crew Transit To Mars

Phase (2) begins with the launch of the six crewmembers. In this phase a launch vehicle (e.g. Soyuz) transports the crew to the ISS. The third BNTR elements will be launched on two additional Energia boosters to rendezvous with the ISS in early 2024 for on orbit assembly and checkout. The Transit Habitat joins with the Mars Transfer Vehicle for a departure on October 17, 2024. In the 180-day transit to Mars, the BNTR provides thrust for all burns and electrical power. The nominal arrival date is April 15, 2025. Upon arrival to Mars, a propulsive burn puts the vehicle into orbit. The crew performs a rendezvous maneuver with the Mars Habitat/Lander waiting in orbit, then a propulsive burn de-orbits the lander and it parachutes down to the Mars landing site where the crew will stay for 535 Earth days. Constant Earth and Mars base communication is provided by communication satellites, and travel around the site is made easier by one pressurized rover that also serve as a “safe haven” if needed.

Once the crew arrives, they find all the needed supplies waiting and the return vehicle prepared to launch if necessary. The crew will then begin scientific measurement of the local terrain searching for signs of water in the vicinity. With the arrival of the supply vehicles from Phase 1, two rovers were deployed and sent to explore the region. The rovers marked sites of interest, and the astronauts can explore the surface with these vehicles. The astronauts will collect samples and explore the region until the time of the return trip to Earth.

2.4 Phase 3: Crew Transit Return to Earth

Phase (3) consists on the return of the crew to Earth. In this phase the crew members, with return samples, board the MAV and depart Mars surface to rendezvous with the Transit Habitat left in Mars orbit. The crew will then depart on a 180-day journey to Earth. Mars orbit departure is nominally on October 2, 2026. Upon arrival at Earth orbit, the crew could either perform a ballistic entry to Earth, or dock at the ISS for systems and crew checkout prior to Earth entry. Earth arrival date is expected on March 31, 2027 translating into a nominal 895-day mission for the crew.

3. PHASE 1 SYSTEM COMPONENTS

The main robotic section of the mission is in Phase 1 where various systems perform either autonomous or remote operations in orbit and/or on the surface of Mars.

3.1 Habitat/Lander

The habitat can land using an autonomous landing sequence or with manual control to the Martian surface. Serving as research center, storage space, exercise room and general living space, the habitat is a multi-functional facility that the crew will call home for the mission duration.

The first floor is mission oriented, with storage, exercise, scientific laboratory, and interplanetary and Martian communications areas. Upper floor is the individual crew living quarters with a common meeting area, totaling approximately 900 m^3.

Structurally, the habitat will appear vertically cylindrical in external appearance with a diameter of 7.5m.

3.2 Communication Elements

Every crewmember will have two-way voice and data communication capability with the habitat and any location on the Martian surface. For this to occur, every rover, environmental suit and the MAV will have powered communication equipment.

For communication with Earth, the habitat communication will relay relevant information to one of the on-orbit communication elements. Included with the CLV element is a communication satellite dedicated to transmitting information to Earth. Phased with the two empty CLVs, placed in highly elliptical Molniya orbits as additional data relays, communication blackouts with Earth will be minimized. These high power satellites will provide the power to support mega-bit/second data transfer rates from Earth to Mars. The orbit phasing of these satellites will ensure one is located over the base camp at all times with a 25 degree orbital inclination will be able to maintain a constant contact with Earth and NASA’s Deep Space Network.

Communications and scientific data collection is of crucial note for this mission with an emphasis on looking for signs of water. The communications network will monitor all the elements here and provide a high data rate conduit for all future astronaut communications.

3.3 Crew Comfort Requirements

Although crew comfort may seem secondary to mission objectives, it is critical to maintain crew moral and well-being. Including essential living requirements, the crew will have access to a couple luxuries that serve not only recreational purposes but also supplement the mission at hand.

Each crew member will have access to the following amenities: galley and food, clothing, sleep accommodations, crew health care, personal hygiene, waste collection, housekeeping, operations, maintenance, recreation and photography [2,6].

3.4 Nuclear Power Option

The TMI elements and habitats require a large power supply to operate at the levels needed for this mission. To ensure a short travel time to Mars a high power propulsion system is required to transport the mission elements. In designing the power systems for this mission several options were investigated. For the propulsion systems onboard the space craft both chemical and nuclear power were considered. To provide electrical power to the spacecraft and during the planetary stay on Mars chemical, nuclear, and solar systems were considered. In order to minimize the zero gravity exposure time for the crew a high power system is need to keep the travel time to 180 days. Chemical propulsion methods were considered as a long standing proven technology for interplanetary travel. In design of the mission it was realized that an enormous amount of propellant would be needed for the required maneuvers. Propellant consumption rates would be very high requiring the vehicle to keep empty tanks for a large portion of the mission. Additionally this method would only provide propulsion for the craft; an additional system would be needed to power the communications equipment. In comparison, use of the BNTR element would reduce the amount of needed propellant for the required maneuvers and also provide the high power necessary for data transmission. Use of the BNTR for all the mission elements builds additional levels of reliability in the system and matures the technology from the cargo supply to the crew launch. Nuclear power was chosen here as it provides a low maintenance system to provide the needed power. Solar panels are also capable of generating the needed power, however to develop a system to generate this much, would require a giant solar farm area on Mars, that is unfeasible to develop.

For the TMI of the cargo and later crewed components, chemical propulsion methods were considered as a long standing proven technology for interplanetary travel. In design of the mission it was realized that an enormous amount of propellant would be needed for the required maneuvers. Propellant consumption rates would be very high requiring the vehicle to keep empty tanks for a large portion of the mission. Additionally this method would only provide propulsion for the craft, an additional system would be needed to power the communications equipment. In comparison, use of the BNTR element would reduce the amount of needed propellant for the required maneuvers and also provide the high power necessary for data transmission.

Mission requirements for the crew establish very high power needs to operate all the scientific equipment propellant generation systems and communications system. Chemical systems would require a significant amount of additional propellant for the mission timeline. Nuclear power on Mars will deliver the required power, generate the mission propellant supply and provide for the astronauts needs.

3.5 Bimodal Nuclear Thermal Reactor Design

The design for the BNTR's to deliver the cargo and manned elements to Mars is based on Fusselman's design [7]. The key design parameters used in the sizing of this system are summarized in Table 1. Each CTV will consist of three BNTR's to allow for system redundancy in case of an "engine out" failure. This configuration will deliver the needed power for high thrust propulsion, TMI maneuvers, course corrections, and electrical power for the communication satellites.

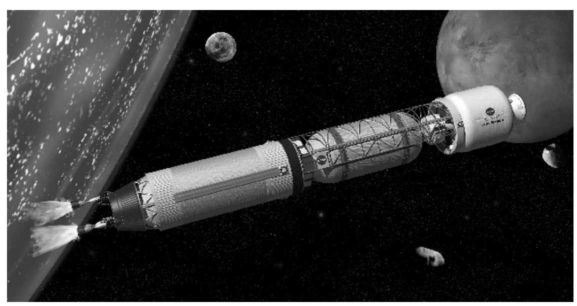

Fig. 2. NASA Glenn Research Center Concept for BNTR Vehicle [8]

For the propulsion element of the Crew Transfer Vehicle design, it has been proposed to use Bi-Modal Nuclear Thermal Rockets (BNTR). A common BNTR design capable of producing 15klbf and 50 kilowatts of electrical power is used for both the supply and the crewed Mars flight. Use of the BNTR for the cargo mission validates the concept and reduces overall program cost through use of a common space propulsion system. The BNTR used for the manned crew also includes additional radiation shielding. The BNTR provides the thrust for the TMI & TEI maneuvers, all mid course corrections and electrical power during transit.

The bimodal core stage is a closed Brayton cycle power conversion system that uses one 25 kW Brayton rotating unit for each of three reactors. Each reactor is operated at 2/3 capacity to ensure the mission can be accomplished with one "engine-out". High pressure hydrogen propellant is used for active cooling of the reactor, and then to drive the turbine for electrical power. The exhaust is routed through the reactor core's fuel elements absorbing energy released by fissioning uranium atoms. The superheated propellant is expanded out a supersonic nozzle for thrust.

Table 1. BNTR Design Parameters

Parameter	Value
NTR Thrust	15,000 lbf
Core Thermal Power	313.2 MWt
NTR Specific Impulse	863.7 sec
Brayton Cycle Net Power	37 kWe
BNTR Mass each	6,744 lbm (3,059 kg)
BNTR Length	448" (11.4 m)
NTR Nozzle Exit Diameter	54" (1.4 m)

3.6 Mars Terrestrial Power Supply

Once on Mars the astronauts will need a robust power supply, to power the high power elements needed in this mission. This includes the Mars habitat/ laboratory, in-situ propellant for the MAV, light trucks, and communications system. NASA mission requirements for this class of mission require a minimum of 100 kWe for all the elements [9]. CMMP mission concept will employ two 80 kWe nuclear power generators meet the high power mission requirements and be able to operate at a slightly reduced capacity should a power unit fail during the mission. The high power requirements of the propellant generation device make the use of nuclear power plant the best option for this mission.

3.7 Martian In-Situ Propellant Development

Propellant resources are a precious commodity on Mars and will be generated for In-Situ Resource Utilization plant (ISRU) [10]. This plant will run off of a nuclear power plant deployed a distance away and generate methane fuel using the CO_2 in the Mars atmosphere and hydrogen delivered with the supplies; the process will also produce water and oxygen. The methane production shall be completed within twelve months, before the crew mission begins, as a safety precaution.
The methane fuel provided by the ISRU will be used for the light trucks and MAV, as well as oxygen and water for human consumption. The ISRU process is based upon the Sabatier reaction and is expressed as followed:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \qquad (1)$$

The consumables for this process are Hydrogen brought from Earth (about 5 % of the total generated consumable weight) and the abundant Carbon Dioxide in the Martian atmosphere. Electrolysis, decomposes water into $2H_2$ and O_2. This can be combined with the original Sabatier reaction to yield a final ISRU decomposition:

$$3CO_2 + 6H_2 \rightarrow CH_4 + 2CO + 4H_2O \qquad (2)$$

yielding an Oxygen to Methane output ratio of 4:1 and therefore giving a propellant mass leveraging of 18:1 along with a large quantity water as a bi-product. When combined with hydrogen from Earth, the Martian environment will be able to provide propellant for the Mars Ascent Vehicle (MAV) to return to orbit and fuel for the light trucks to transport the crew over the surface of Mars. The propellant generation process will be remotely started upon the arrival of the cargo to Mars. Propellant generation will be monitored from Earth and be completed prior to the crew launch to Mars. This process will take approximately one year and is a high power draw mission element, thus the need for the supplemental planetary power supply.

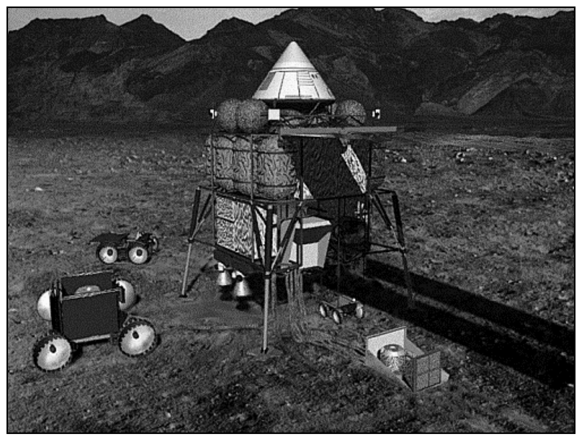

Fig. 3. MAV and Integrated ISRU [5]

Martian planetary propellant generation will yield a significant mission weight benefit. Propellant for the return mission will not need to be carried to Mars first reducing the launch payload. Setup of a Martian propellant generation facility will allow future missions to build on from the basic facilities here. Only future re-supply of the hydrogen reactant is needed to generate more propellant reserves on Mars.

3.8 Mars Transportation Supply

All orbital assembly and packaging will be done in the proximity of the ISS for human supervision and assurance. The vehicle orbiting Mars will be the surface habitat that will also serve as the Mars Lander when the crew arrives. The vehicle landing on mars will carry the bulk of the supplies including a MAV and what has become a staple of sorts in current Mars mission concepts, an ISRU. The MAV is an Apollo type spacecraft capsule that returns the crew to the CTV from the Martian surface. Initially this vehicle is an integral part of the ISRU. As the ISRU generates methane, it is pumped directly into the MAV fuel tanks eliminating dangerous human interaction to transfer fuel from the ISRU to the MAV. The ISRU/MAV interface structure allows the MAV to launch from directly on top of the ISRU platform without damaging the ISRU's operational capability.

The Cargo Lander (CL) landing will position the ISRU un-fueled MAV combination, feedstock, nuclear power integrated on top of its robotic truck, and two un-pressurized rovers near the planned human landing site. The robotic truck will drive the power plant several hundred meters from the base, connected by flexible cabling.

Included in the Cargo Supply mission is an atmospheric blimp. It will inflate on the surface and fly over the Martian terrain. Attached to the blimp is a mini-rover with a small science package that is capable of air, soil, and liquid measurements. This blimp will explore the region around the habitat and report back any sites of interest to Earth that the crew can later explore upon arrival in more detail. Activated at arrival of the cargo elements the blimp will be able to scout $1km^2$ per day and will operate for the entire mission lifetime continuously investigating the Martian surface.

A baseline 535 day stay emphasizing in search for water/ice either sub-surface or on the surface, additionally intensive scientific research in geological, atmospheric, biochemistry and human-medical areas will be conducted by the entire crew. Following the 535 day mission, the crew and return samples will board the MAV and prepare to rendezvous with the CTV (same vehicle used in the outbound leg). Once docked, the crew will transfer to the habitat module in the Earth Return Vehicle (ERV) and begin the Trans-Earth Injection (TEI) phase. Before arrival at Earth, the crew transfers into the MAV and separates from the ERV.

3.9 Rovers

Three Martian rovers, each capable of traversing more than 500 kilometers radius from the base, will be used to explore the surrounding area for existence of water, proof of past or present life forms, and general geological and atmospheric studies. Two will be un-pressurized similar to the original moon rovers, with the third rover being pressurized for further missions from base camp and can be used by the crew as a temporary safe haven. Range can easily be improved by adding additional fuel storage. Each Rover weighs approximately 0.55 metric tons and uses an internal combustion engine, generating 65 horsepower. The engines run on methane fuel, generated from the ISRU, with an inert buffer of carbon dioxide. Fuel consumption is on the order of 0.5kg bi-prop per kilometer.

Fig. 5. Conceptual Rendering of Pressurized Martian Rover Docked to Habitat [5]

4.0 TRADE STUDIES

Several trade studies were performed to optimize system drivers derived from mission requirements.

4.1 Mission System Mass Breakdown

The elements used in this mission were sized from reference numbers in *NASA Reference Mission* [9]. Major system components have been includes here to give scope to the sizes and payload requirements needed for this mission.

Table 2. Mission System Masses

Cargo Transfer Vehicle 1 Mass Breakdown		
Cargo Lander Payload Mass	**50024**	**kg**
Mars Ascent Capsule	4829	kg
ISRU plant	3941	kg
Hydrogen feedstock	5420	kg
3 teleoperable science rovers	1500	kg
Entry System Masses	**23333**	**kg**
Total BNTR Mass	**23400**	**kg**
TMI Propellant Mass	**54931**	**kg**
TOTAL INITIAL MASS (IMLEO)	**156947**	**kg**
Cargo Transfer Vehicle 2 Mass Breakdown		
Habitat Element	**29105**	**kg**
80 kW nuclear power plant	5713	kg
Unpressurized rover	550	kg
Crew Vehicle Payload Mass	**37591**	**kg**
Landing System Masses	**4204**	**kg**
NTR Propulsion System	**23400**	**kg**
TMI Propellant	**48922**	**kg**
TOTAL INITIAL MASS (IMLEO)	**139778**	**kg**

4.2 Mission Trajectories

Both cargo and crew vehicles will use conjunction type trajectories between Earth and Mars. These minimum energy trajectories are constrained so that the arrival entry speed at Mars for both vehicles does not exceed 8.7 km/s (corresponds to a hyperbolic excess velocity of 7.167 km/s) and that the crewed transfer vehicle does not have an arrival entry speed at Earth exceeding 14.5 km/s (corresponding to a hyperbolic excess velocity of 9.36 km/s). The crewed trajectories are further optimized to a maximum transit time of 180 days. Due to the synodic period between Earth and Mars, the minimum time between transits requires that the crew remain on the surface of Mars for nearly one-and-a-half Earth years. However, this relatively long stay time can be used to maximize the potential for scientific return.

4.3 Landing Site

Both the cargo vehicles and the crewed vehicle arriving two years later will enter orbit at Mars while the southern hemisphere is in its winter. Based upon NASA Ames Mars General Circulation Model (MGCM) simulation of the Martian atmosphere, the winter hemisphere develops a strong polar jet stream which drives that hemisphere to have relatively higher wind speeds on a large scale, while the opposite hemisphere is relatively quiescent near the pole [11]. Winds in portions of the middle northern latitudes may also exceed landing criteria as a result of persistent climatological circulations as the season progresses.

The declinations for the arrival trajectories favor a more equatorial landing site, while the criteria for finding water favors a landing site above 50^{o} N latitude based upon the Gamma Ray Spectrometer (GRS) data. However, planetary protection constraints may preclude visiting sites, which may provide viable habitats for Earth organisms.

The tentative landing site selected is near the resting place of the Viking 1 Lander on Chryse Planitia (22.5^{o} W, 47.8^{o} N). This site was selected because a large amount of data has been accumulated on it from Viking 1 and other unmanned probes. Since the site's environmental characteristics are well understood, its choice provides a greater measure of crew safety, as well as opportunity to perform well-conceived science. The area is also considered to have great historical and public interest value because of Viking 1 remains.

As the data from current and future Mars missions are analyzed and the current design is further refined, it is expected that alternative landing sites will be developed.

4.4 International Space Station

The International Space Station is a keystone for this mission. With its completion by the retirement of the Space Shuttle, the fully functional station will be able to serve as a stepping-stone to the planets and beyond. Exploration of the solar systems cannot be achieved by a single nation. With the ISS many countries will be able to contribute to the future exploration of space. For the CMMP the ISS will serve as the launching point from Earth, complex launch systems will be tested, evaluated, and undergo final assembly before being launched to Mars. The hardest part of the launch process getting off the surface is already complete and from there interplanetary vehicle can re-supply at the ISS before departing. Materials can be supplied to the ISS in small launches and assembled in orbit to develop future spacecraft. Research into new construction techniques and materials can be developed in the near zero- gravity environment. Further understanding of the effects of long term space exposure can be better understood and treated to keep our astronauts safe for long interplanetary missions. As a fully operational space station the ISS can serve as a permanent docking station for all future missions and allow the crew to launch to and from Earth as necessary. Acting as a bridging point between the chemical launch vehicles from Earth and the high power nuclear vehicles needed for long duration space missions, the ISS will be a key component in all future missions.

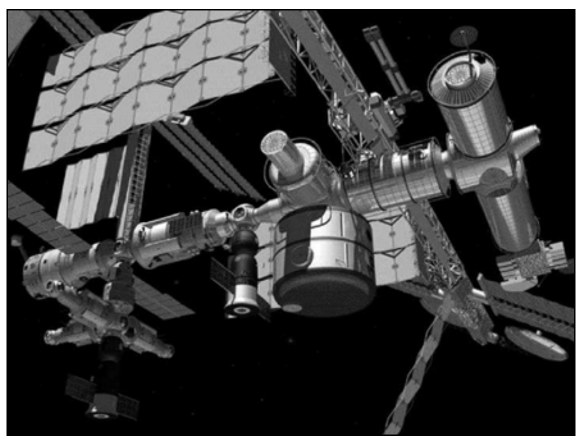

Fig. 6. NASA Design Reference Mission Mars Habitat Concept Rendering at ISS [5]

5.0 CONCLUSION

As a system level solution, CMMP can enable future interplanetary explorers with the tools, techniques, and technology to reach other planetary bodies within the solar system, provide insight into its origin, and possibilities for the future of humanity.

Please note that all images of vehicles and equipment are conceptual artists' renderings and are not representations of the final product for this mission.

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